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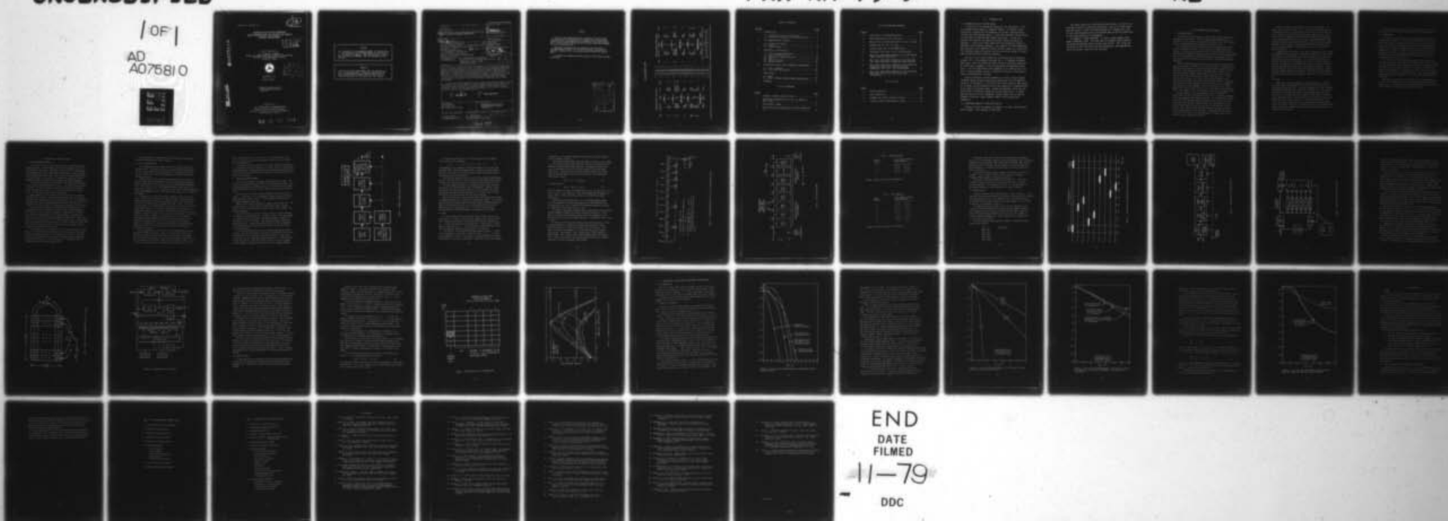

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POTENTIAL USE OF HIGH FREQUENCY DATA TRANSMISSION FOR OCEANIC AIR TRAFFIC CONTROL IMPROVEMENT

Martin Nesenbergs

U.S. DEPARTMENT OF COMMERCE
NATIONAL TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION
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16. Abstract

This report is concerned with the transatlantic Air Traffic Control (ATC) data links in the high frequency (HF) band. The report tries to broaden the appropriate communication system concepts by fortifying them with general parametric objectives. While such a broad approach cannot escape practical constraints and reductions, especially in eventual design and implementation stages, it is nevertheless a useful tool here. It leads one to characterize the HF propagation medium more fully. This in turn enables one to conceive data communications outlines with more advanced structures and with emphasis on exploiting the latest technology, both hardware and software.

A full study should go beyond this initial effort and incorporate several system alternatives, plus their tradeoffs in terms of objective gains versus system costs. This brief report concludes with a parametric summary of ATC HF channel issues, operational factors, and the importance of performance specification. Pertinent unresolved issues are also listed at the end.

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Preface

As part of the increasing concern to improve air traffic control of oceanic regions, the Department of Transportation's Transportation Systems Center is investigating various methods to effect such improvement. One such method involves the use of HF data transmissions between aircraft and ground stations.

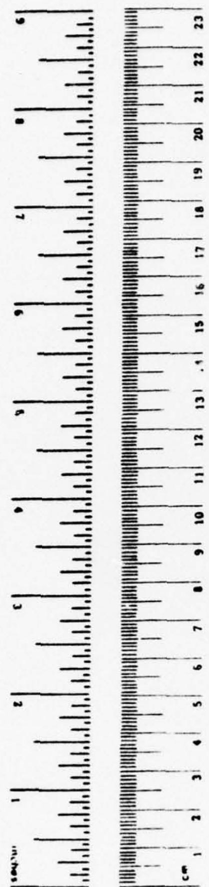
The report presented herein was prepared by the Institute for Telecommunication Sciences. It is one of two reports describing the potential usefulness of HF data transmissions for oceanic ATC improvement.

The report was completed under the direction of TSC Project Engineer, Leslie Klein.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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1. INTRODUCTION

1.1 PARAMETERIC VIEW OF SYSTEM ISSUES

In the world of HF systems two conclusions are inescapable. First, he HF communications medium is extremely complex. For digital signal transmission, propagation, and reception, the channel characterization involves many time-varying factors. If not used optimally, the HF medium can cause many dissatisfied data communication users. Second, the physical and statistical HF behavior has been studied by numerous researchers. A long list of both theoretical and experimental studies is reflected in the attached references. The scope of this short memorandum does not permit us to summarize the past HF work, except in a cursory way. The interested reader is urged to turn to the available wealth of literature to acquaint himself with the HF medium.

The rest of this section emphasizes a particular way of looking at systems; this is the parametric approach and it is attempted throughout this study. With this method one simply strives to represent everything of significance systemwise in terms of measurable and meaningful parameters. Just like nomenclature, the parameter set is seldom unique. But that is a mear nuisance, and not a substantial obstacle, to the study of typical telecommunication systems.

When one recognizes certain parameters as crucial, choices between different complex system versions may be made on the basis of numerical values of said parameters. For the ATC (Air Traffic Control) data system, for instance, one key parameter could be the probability of message blocking or that of intolerable delay. Another key parameter could very well be the total installation, operation, and maintenance cost. If these were the only two cruicial parameters, system issues could be resolved through a relatively simple tradeoff process involving these two parameters.

1.2 FROM BROAD CONCEPTS TO PRACTICAL REALITY

Another principle of approach to systems is to start with relatively broad concepts. This approach is taken here.

One simply starts with a sufficiently broad premise, in order not to overlook an obscure but promising alternative. One is, of course, cognizant that sooner or later the system designer will encounter real life. At that time the generality will be narrowed down to realistic dimensions, or the system concept will be abandoned.

An example is signal bandwidth. To start, system concepts could permit bandwidths in MHz. But later facts of frequency band allocation may bring the bandwidth down to no more than 100 kHz. And, if one cannot afford to part with existing 25 kHz transceivers, the bandwidth may end up at 25 kHz or even the 3 kHz voiceband.

2. THE COMMUNICATIONS CHANNELS

2.1 PROPAGATION MEDIUM

The transatlantic ATC system has several single sideband (SSB) channel assignments in the HF band. The ATC HF band transmitters/receivers are tunable from 2.8 to 24 MHz, or equivalently from nearly 10 to 100 m in wavelength. The SSB modems occupy a nominal voiceband of 3 kHz.

The HF medium has been used extensively for long distance data transmissions throughout the world. By long distance, one means 1000 km and farther. The typically achieved data rates vary from less than 100 b/s for old-fashioned telegraphy to several thousand bits per second for more advanced data links. Unfortunately, the higher the keying rate, the more the data links are restricted in distance and are subject to unfavorable propagation conditions.

The HF propagation medium is strongly associated with the ionosphere. Both vary with time in a fashion that is hard to predict. The physical and statistical characteristics of the ionosphere and the HF channels have been described by many (National Bureau of Standards, 1948; Grisdale, et al., 1957; Davies, 1965; Goldberg, 1966; Betts, 1975; Filter, et al., 1978). Several workers have offered useful HF models (Watterson, et al., 1970; Watterson and Minister, 1975; Ziemer, 1976; Bello and Goldfein, 1977). Others have placed emphasis on the data transmission effects of the medium, including signal design, modulation, coding, diversity, and so on (Bello, 1965; Nesenbergs, 1967; McManamon, et al., 1970; Pierce, et al., 1970; Brayer, 1971; Kuba and Lowry, 1971; de Lellis and Michelson, 1975; Harper, et al., 1975; Foshee, 1977; Hillam and Gott, 1978; Kwon and Shehadeh, 1978).

The key features of HF can be summarized here. In absence of other signals or noise, the ionosphere causes signal distortions associated with wave propagation and multipath conditions. Two phenomena are observed. First, the signal amplitude fades up and down at the receiver input, and, second, the received signal tends to suffer time (delay spread) and frequency (Doppler spread) distortions that tend to mutilate even strong signals. Both amplitude fades and time-frequency distortions are caused by multipath conditions in the ionosphere. These conditions can be less severe at certain times and in given locations, but their overall effect must be viewed as randomly time-variant.

The depth of fades can occasionally be in the 20-30 dB range. The longer fades tend to last about 1-5 sec. They cause error bursts that are of comparable duration. The multiplicative distortions, on the other hand, tend to cause more actual delay distortion than frequency spread. Delays of 1-10 ms are not uncommon. The main feature of these delay distortions is that they do not stay fixed for very long. Associated with their rapid variation, frequency spreads and shifts of the order of a hertz are common. Techniques such as automatic adaptive equalization have not been successful on HF channels because of the rapidity and instability of channel response variations.

To communicate reliably over HF, the above references show that a large time-bandwidth product is needed in the digital signal design. For example, the keying rate in the modulator should be sufficiently low to avoid crippling effects by the multipath spread. Bit or character interleaving of an individual code word should extend over 20-30 sec to avoid a fadeout of the word. Spreading over a bandwidth that exceeds the correlation band of the distortion also helps protect the signals against multipaths. Multiple or M-ary Frequency Shift Keying (MFSK) techniques are perhaps the simplest and most economic techniques to implement. They offer arbitrary bandwidth expansion and phase distortion insensitive operation in a relatively simple way.

2.2 NOISE

Three types of noise are observed in any radio receiver. They are the thermal noise, the atmospheric noise (CCIR, 1964) and man-made noise (Spaulding and Middleton, 1977). With the improvement in low-noise receivers and enhanced transmitter power capability, the thermal (i.e., the familiar Gaussian) noise has apparently become the least bothersome of the three noises at HF. The other two noises, whether they are caused by lightning in the atmospheric case, or by various emissions of electrical devices, are quite spiky or impulsive in character. Their time duration tends to be short. Thus their overall effect can be substantially reduced by proper HF receiver filters. Moreover, the spurious emissions from man-made sources can be alleviated by engineering layouts of the HF receiver stations with respect to their environs.

In summary, the HF radio noise effects appear insignificant when contrasted with the serious multipath distortions for the data channels.

2.3 INTERFERENCES

In the absence of desired signal, the transoceanic HF bands tend to contain undesired signals. These undesired signals seem to offer a far more serious problem to data quality than does the previously mentioned noise. The totality of undesired radio signals is called interference. Interference to Atlantic ATC ground stations is apt to be generated by worldwide (e.g., Pacific, European, etc.) ATC transmissions. Because of unpredictable ionospheric propagation conditions, some far away (e.g., 10,000 km) HF paths may encounter higher propagation gain than does the desired HF line (e.g., 1,000 km).

The effects of similarly modulated co-channel interference are far from fully understood. One expects false frequency locks, clock acquisition problems, plus general error probability deterioration. Depending on relative power levels and spectral properties, the effects could vary from drastic to insignificant. The interference format, such as CW or pulsed waves, could also affect the system performance. This has been reported in unpublished reports (M. Nesenbergs, et al., OTM-89; Akima and Nesenbergs, OTM-73-123).

When desired and undesired signal waveforms are indistinquishable, the classical orthogonality properties cannot be used to eliminate interference effects. However, additional bandwidth capability can be beneficial to better capture the supposedly stronger desired signal.

3. CONCEPTUAL SYSTEM OUTLINE

3.1 TIME AND BANDWIDTH SPREAD

As indicated in the preceding section, the HF signal suffers random distortions that, if severe enough, cause bit and character errors in the received data. Binary error rate (BER) in excess of 10^{-3} is intolerable in many applications, and it should be avoided for ATC. Short of seeking other communications media, such as VHF or satellites, there appears to be only one HF remedy. That remedy is to expand sufficiently the time and frequency product of the signal, and to process the received waveform.

To reduce the multipath delay distortion of individual keyed waveforms (bauds), assume a waveform duration of 20 ms. This limits the keying rate to 50 baud. To further lessen the impact of received phase fluctuation, assume a non-coherent receiver, i.e., a receiver that does not observe, track, or in any way use received phase information.

Assume, however, that the ground station HF receivers do track the received carrier frequency. When done non-coherently, this is equivalent to amplitude or energy detection at certain spectral lines. At the suggested low keying rate, such operation appears possible with the Fast Fourier Transform (FFT) spectral analyzer (Chadwick and Springett, 1970; Ali, 1978).

Let the signal spectrum occupy a bandwidth not exceeding 3 kHz. For 50 baud keying, this is around 50 times the minimum required bandwidth. Thus, there is room for spectral spreading via signal design. (Later, we shall outline an MFSK approach for this signal design.) Note that the 3 kHz does not exceed the standard voiceband on terrestrial and other links. Also, if a wider total band -- such as between 25 and 50 kHz -- were available to ATC on international worldwide bases, it could be slotted and regionalized into several voiceband strategies. Multiple access and reduced HF interference could be engineered accordingly.

The ATC messages may be divided into bit or character groupings, called words. If detected and processed individually, these words could be badly distorted or even entirely lost if they happened to fall into a deep fade. To avoid this, assume that each data word is somehow expanded to span much more than a fade duration. Such word expansion is conveniently done by a process known as interleaving (Ramsey, 1970).

Interleaving will be introduced in the next sections in conjunction with block coding for error control purposes.

3.2 ROLE OF ERROR CONTROL

As indicated above, data transmission over HF tends to suffer from too many errors. This seems to be the case despite optimal signal design, the best state-of-the-art transmitter/receiver configurations that money can buy, and the use of the latest propagation predictions for path and frequency selection.

Numerous workers have studied HF and related media error statistics and have sought ways of reducing their impact on transmitted data messages (Brayer and Cardinale, 1967; Cohn, et al., 1968; Crowley, 1969; McManamon, et al., 1970; Pierce, et al., 1970; Reed and Blasbalg, 1970; Brayer, 1971; Chien, 1971; Juroshek, et al., 1971; Kuba and Lowry, 1971; Kirby and Nesenbergs, 1972; Prapinmongkolkarn, et al., 1974; Chase, 1975, Butman, et al., 1975; and many others).

The following is a brief error control summary for ATC-type HF data links. Forward error correction (FEC) does not appear to have any decided advantage over automatic repeat request (ARQ) schemes, unless the feedback links are either unavailable or extremely difficult. (Note: For ATC one can assume primary FEC responsiblity with optional and limited other channel or hybrid ARQ backup.) For relatively short messages, convolutional or concatenated codes appear unnecessary. This leaves block codes as a primary candidate. Among block codes, the long codes are only slightly more effective than shorter codes. Moreover, the longer the code, the more involved its decoding process, especially when soft instead of hard decisions are permitted. Long codes also do not fit the relatively short message formats envisioned for ATC. The error control power of the shorter block codes over HF links can be significantly increased with the previously mentioned interleaving.

For the transoceanic HF links, given all their application constraints and channel statistics, one may consider a relatively short block code, heavily interleaved, and working primarily in the FEC mode. Golay code (23, 12) could be a reasonable first example, followed by a modified (24, 12) Golay code (Golay, 1949; Gallager, 1968; Peterson and Weldon, 1972). Since in the (n,k) notation there are k information bits among n total bits per

word, the modified code is exactly rate 1/2. The additional parity bit (i.e., the 24th bit) offers several options of extra parity verification for limited ARQ backup.

To overcome the deep and long HF signal fades, each Golay code word has to be interleaved with other code words. The total span of an interleaved code word should be considerably longer than the previously mentioned 5 sec. In the more detailed system outline to follow, an interleaving span of 25-30 sec will be illustrated

3.3 *TRANSMITTER ABOARD AIRCRAFT*

This section outlines a transmitter system aboard an aircraft. The system is an example embodiment of the issues and constraints faced. Using this prototype system as a strawman, one is in a better position to understand the tradeoffs and to make choices towards finalizing system alternatives.

An outline of the transmit terminal aboard an aircraft is given in Figure 1. The original data is generated as needed and stored in the aircraft data source buffer. There are either automatic or manual ways of initiating a message transmission.

When an order to send is given, the transmit control takes over. The transmit control is scanned through a predetermined routine, perhaps with the aid of a micro-processor and with various clocks, triggers, and monitoring elements.

One of the first tasks of the transmit control is to gate a message out from the aircraft data source. As shown in Figure 1, the unit message is assumed to consist of 240 bits. The 240-bit message is gated to the interleaver and (24, 12) encoder. The interleaver-encoder performs two functions at once. It both encodes the 240 data bits into 20 codewords and interleaves the code words so that no two bits of the same word are closer than 20 spaces.

The structure and operation of the interleaver-encoder are shown in Figure 2. Here the interleaving or interlacing procedure differs from the more familiar versions (Gallager, 1968; Ramsey, 1970). At each step, 12 parallel bits are loaded into the 240-bit register. It takes 20 steps to load the register. After the 240-bit register is filled, the gated parallel readout is stopped and the actual (24, 12) encoding commences.

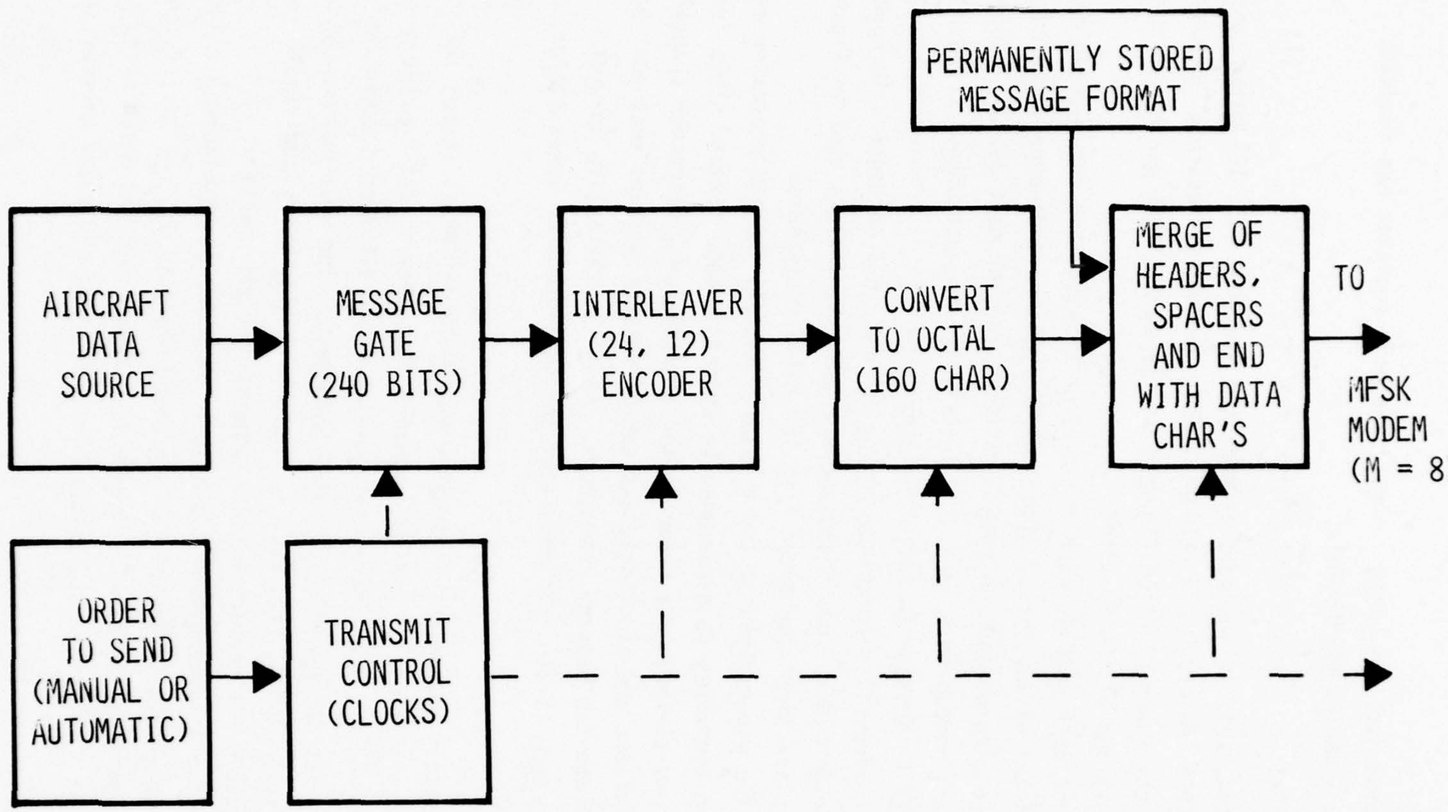


FIGURE 1. TRANSMIT TERMINAL ABOARD AIRCRAFT

The encoder has two parts. First, the main register has feedback taps to form a parity polynomial,

$$h(x) = 1 + x + x^2 + x^3 + x^4 + x^7 + x^{10} + x^{12}. \qquad (1)$$

As implemented, this arrangement encodes the standard (23, 12) Golay code (Gallager, 1968; Peterson and Weldon, 1972). A single, separate 20-stage register at the lower right of Figure 2 merely adds a 24th parity check to each and every one of the 20 words.

Note that each encoded word consists of 24 bits, and the encoded message contains a total of 480 bits. After the 480 bits have departed, the encoder registers are cleared and the gates are reset for the next parallel load.

If binary modems were used, the interleaver-encoder output could proceed directly to message formatter and to the modulator. However, Figure 1 assumes that some multi-frequency keying is used in accordance with bandwidth spread considerations discussed earlier. It follows that in Figure 1 the 480 bits are first converted into 160 octal characters.

Under the supervision of the transmit control, the 160-character message is organized according to a permanently stored message format. This includes appropriate multi-frequency headers (for acquisition), character spacers (for carrier reference and clocking), and end of message markers that must be merged with the 160 message characters. Finally, the entire merged message proceeds to the MFSK modulator and subsequent RF power stages.

3.4 MFSK

This section describes a possible M-ary FSK (or MFSK) format for the HF data links. To start, assign a special frequency f_0 for carrier acquisition, reference and tracking. Next, assign eight distinct frequencies f_1, f_2, ..., f_8 for the encoding of data characters. For what one has in mind here, the keying of f_1, f_2, ..., f_8 could initially carry additional information suitable for character clock acquisition and tracking.

To be specific, consider the MFSK message format of Figure 3. A total of nine frequencies is indicated: f_0 (carrier) puls f_1, f_2, ..., f_8 (M=8 keying frequencies for data). The message is started and ended by f_0 tones of durations $T_C + T_D$ and T_E, respectively. Relatively short carrier segments

of duration T_D are inserted between M-ary characters to provide frequency drift or Doppler correction.

There are two types of M-ary characters shown in Figure 3, all of length T_C. First, there are four header characters whose job is to enable initial character and keying (baud) synchronization. (Subsequent so-called "bit-sync" is maintained with the aid of Doppler spacers T_D and baud keying transitions.) Second, there are 160 data characters shown in the figure. With the octal encoding of the half-rate (24,12) code, the MFSK message shown contains exactly

$$160 \cdot 3 \cdot \frac{1}{2} = 240 \text{ bits}, \qquad (2)$$

in a total time of

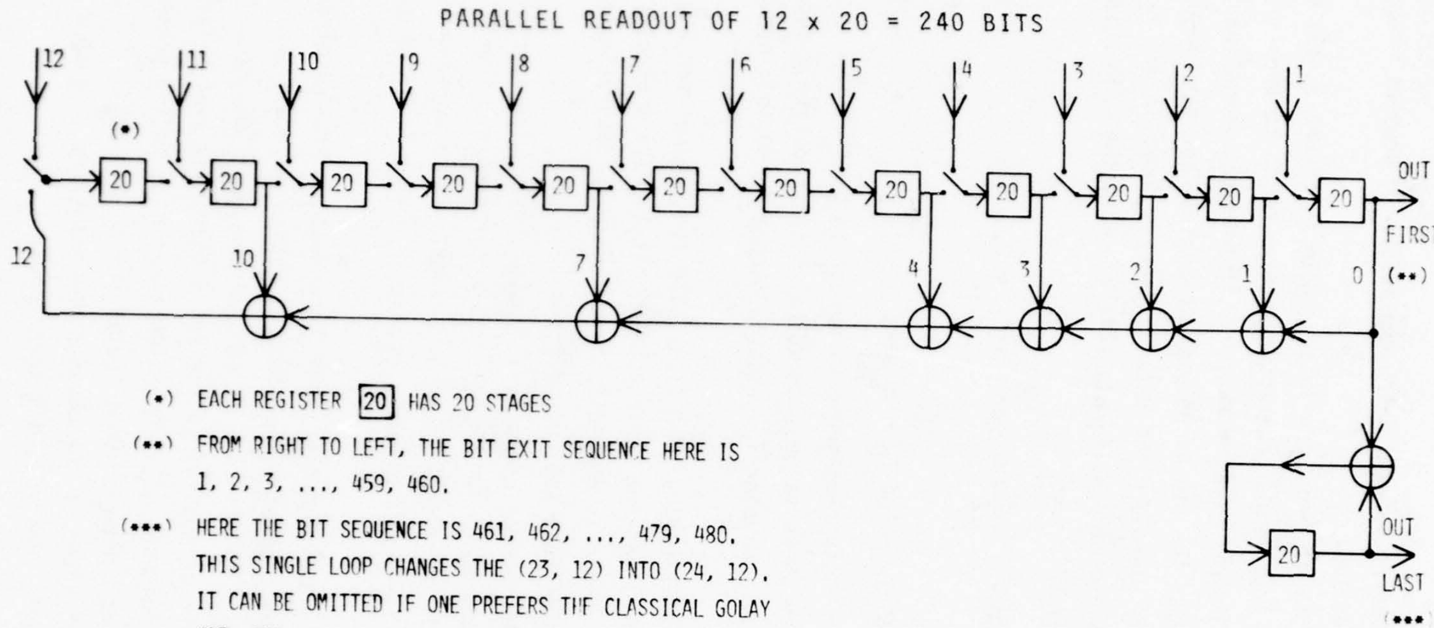
$$165\ T_C + 164\ T_D + T_E \text{ sec}. \qquad (3)$$

Realistic numbers for these time segments appear to be $T_C = 160$ ms, $T_D = 20$ ms, and $T_E = 80$ ms. Given these values, the total message duration adds up to $29.76 \cong 30$ sec. Data, including T_D spacers, occupy 28.80 sec; namely, 96.8 percent.

The code word interleaving span (i.e., the spacing between a given bit in Data Character 1 and the corresponding bit in Data Character 160) is roughly 28.6 sec. This is deemed to offer adequate debursting to errors for individual HF fades that last up to 5 sec.

The format of the header characters may be constructed to provide gradual timing refinement, ending up in complete character and baud lock. Thus, one can use eight (8) key elements, keying exactly one frequency at each time, during the T_C period of a header character. An example of this is shown in Table 1.

The format for the M-ary data characters must also be resolved. There are many alternatives. Perhaps the simplest option would be to assign one uninterrupted $T_C = 160$ ms tone to each of the $M = 8$ choices. These tones, of course, are orthogonal in the sense that they avoid element or baud overlap. The features of such a simple keying - coding scheme are known (Nuttall, 1962; Lindsey, 1965; Chadwick and Springett, 1970; Butman, et al., 1976). Also known is the obvious vulnerability of such a scheme to steady CW or similarly constructed interference.



(*) EACH REGISTER $\boxed{20}$ HAS 20 STAGES

(**) FROM RIGHT TO LEFT, THE BIT EXIT SEQUENCE HERE IS 1, 2, 3, ..., 459, 460.

(***) HERE THE BIT SEQUENCE IS 461, 462, ..., 479, 480. THIS SINGLE LOOP CHANGES THE (23, 12) INTO (24, 12). IT CAN BE OMITTED IF ONE PREFERS THE CLASSICAL GOLAY (23, 12).

FIGURE 2. INTERLEAVER-ENCODER FOR THE (24, 12) MODIFIED GOLAY CODE

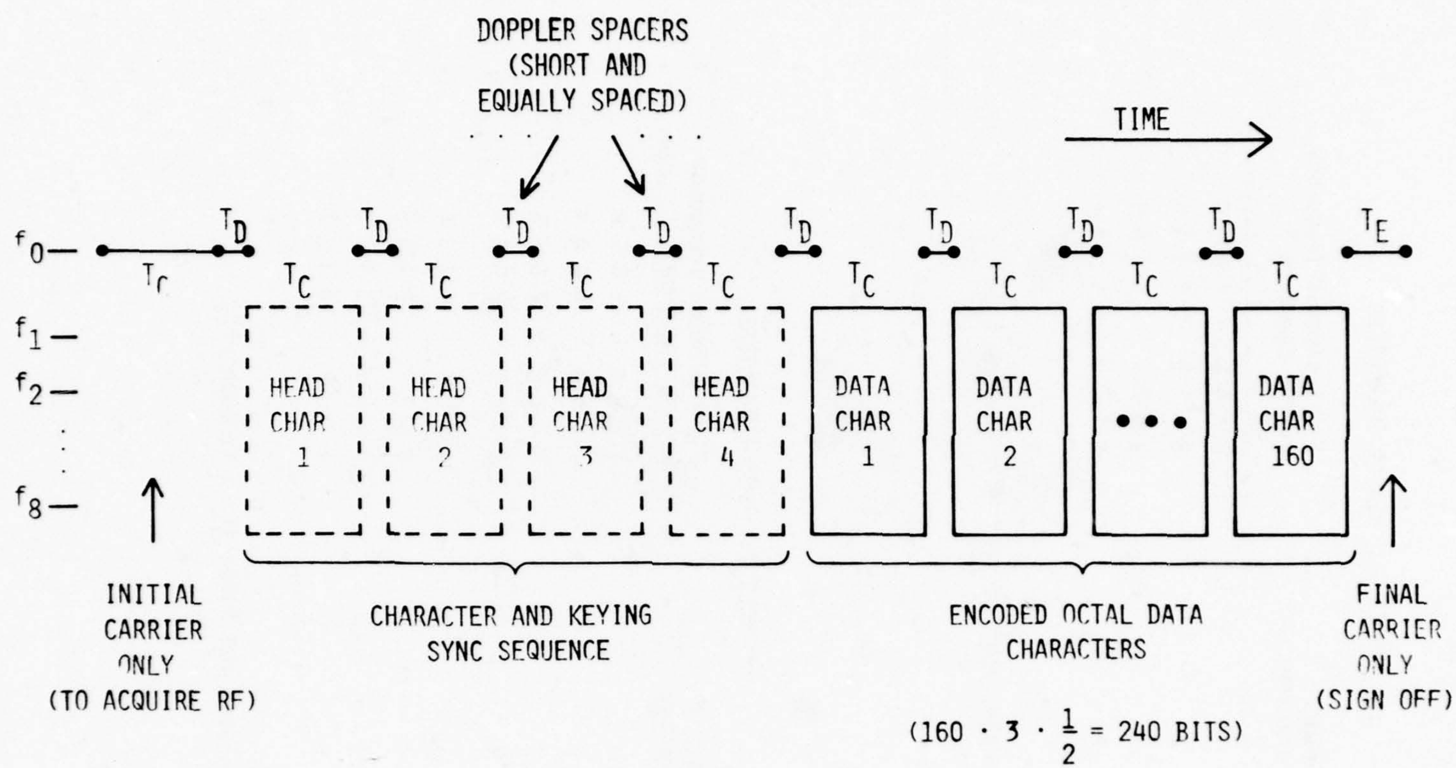


FIGURE 3. MFSK MESSAGE FORMAT

TABLE 1. HEADER CHARACTERS

Header Character #	Eight-element frequency keying sequence *	
1	4 4 4 4	4 4 4 4
2	8 8 8 8	4 4 4 4
3	8 8 2 2	6 6 4 4
4	8 1 7 2	6 3 5 4

*Number j denotes the index of ON-frequency f_j.

TABLE 2. DATA CHARACTERS

Data Character	Eight-element frequency keying sequence*	
1	1 2 3 4	5 6 7 8
2	2 1 4 3	6 5 8 7
3	3 4 1 2	7 8 5 6
4	4 3 2 1	8 7 6 5
5	5 6 7 8	1 2 3 4
6	6 5 8 7	2 1 4 3
7	7 8 5 6	3 4 1 2
8	8 7 6 5	4 3 2 1

*Number j denotes the index of ON-frequency f_j.

Fortunately, there exist various M-ary codes with desired frequency agility for CW interference rejection, and yet with adequate cross-correlation properties (Reed and Solomon, 1960; Golomb, 1964; Berlekamp, 1968; Peterson and Weldon, 1972). When more than one frequency is to be keyed and full MFSK orthogonality is required, then there must be at least 8 keying elements per character.

In the following data character example, let there be 8 key slots or elements. Then, as shown in Table 2, one can construct 8 mutually orthogonal MFSK sequences by a Hadamard-type array.

Each of the 8 frequencies keyed lasts exactly 20 ms. Since there is a total of 8 keys per character, the character lasts for T_C = 160 ms, as indicated before. The frequency foot-print (i.e., the incidence or ON-frequency pattern) of date character #3 is shown in Figure 4.

3.5 GROUND RECEIVER

The basic structure of the ground receiver is given in Figure 5. Since individual aircraft transmissions are 30 sec bursts that may occur at irregular times, message acquisition is an important facet. The functional nature of the MFSK acquisition and carrier tracking stage (namely, the first block of Figure 5) is elaborated in Figure 6.

A frequency tracking loop locks onto the carrier frequency f_0 and corrects incidental frequency drifts caused by both equipment instability and propagation dynamics (Lindsey and Simon, 1973 and 1977). After the initial continual tracking that lasts for 180 ms, the loop transfers to a timed (gated) and sampled mode. In the timed mode, f_0 is observed for 20 ms out of a 180 ms period.

The MFSK character timing progresses through six consecutive stages. They are (see Figure 6):

All	0	correlation	,
4444	4444	"	,
8888	4444	"	,
8822	6644	"	,
8172	6354	"	,
MFSK	Keying	"	.

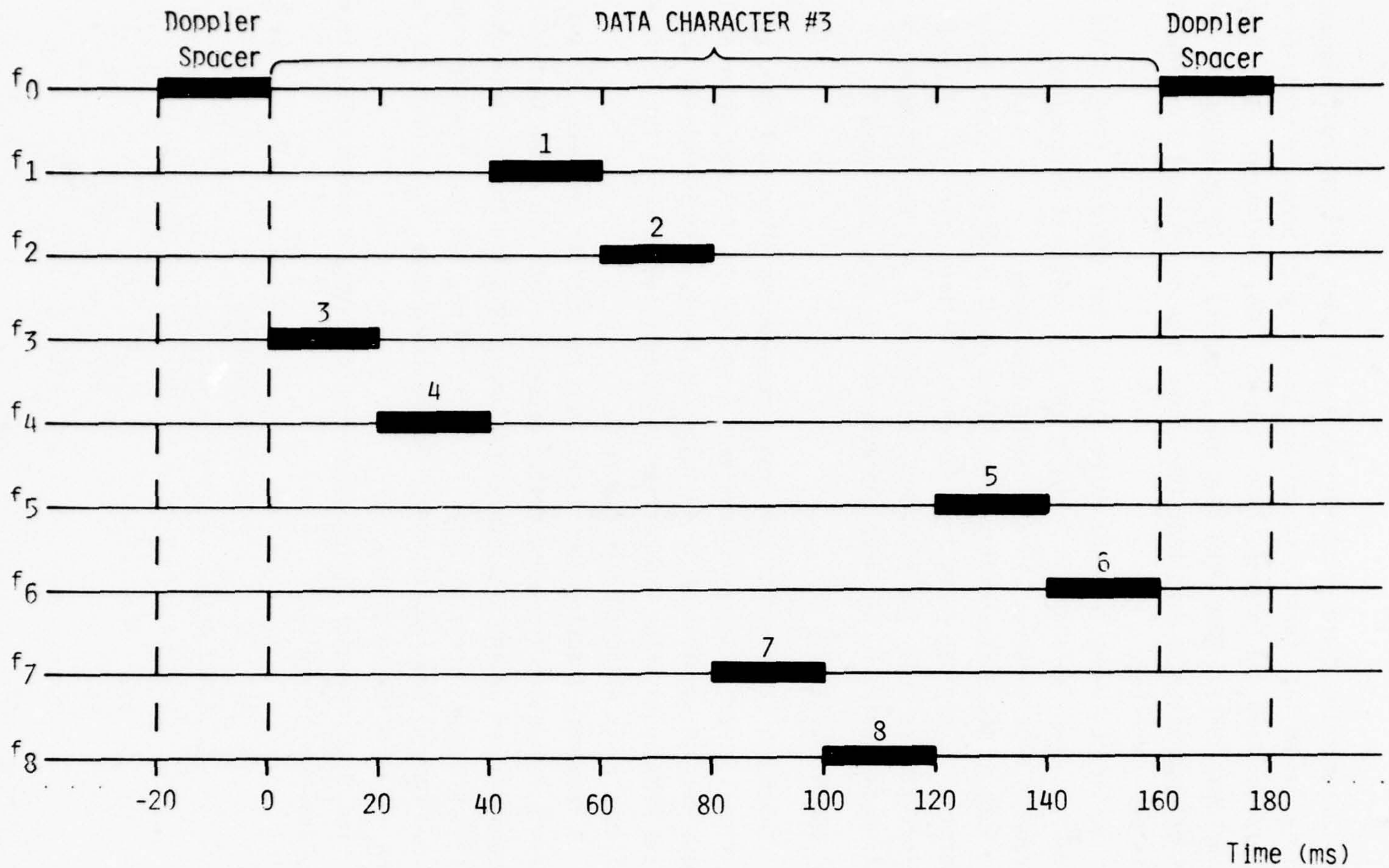


FIGURE 4. THE PATTERN OF ON-FREQUENCIES FOR DATA CHARACTER #3

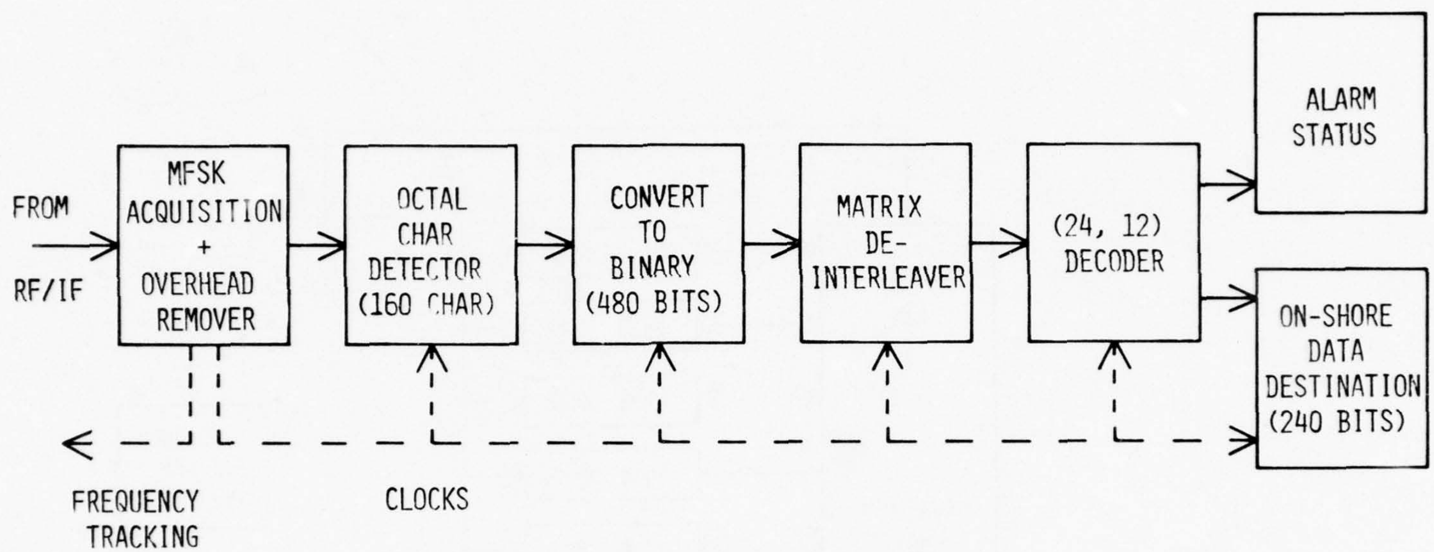


FIGURE 5. STRUCTURE OF THE GROUND RECEIVER

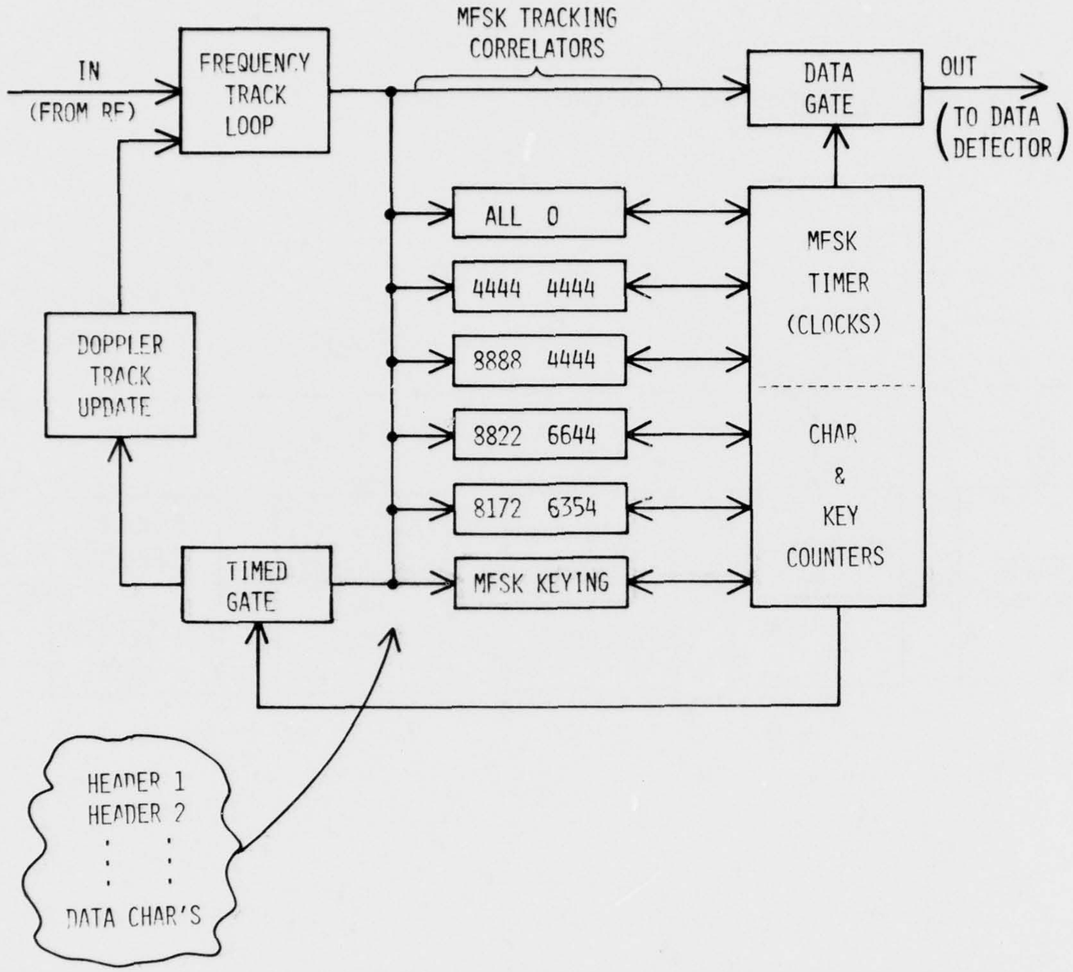


FIGURE 6. MFSK ACQUISITION AT THE RECEIVER

The first five correlators (namely, from All 0 to 8172 6354) are active during the initial preamble only. The sixth correlator (namely, the MFSK keying tracker) is active throughout the message duration. Combined with counters and clocks, it controls gates for data output, as well as for Doppler drift sampling.

After acquisition of the character waveform sequence (it consists of 160 characters), the characters are individually detected in the Octal Character Detector (see Figure 5). There are several issues here. The first problem concerns the so-called hard versus soft decision (Harper, 1974; Chase, 1975; Jewett and Cole, 1978). Several decibels of signal-to-noise (SNR) improvement may be gained by using soft decisions. However, hard decision detectors are simpler to implement. Most present-day systems employ hard decision devices, but this may change in the future.

The second concern deals with the functional structure of the coherent vs. partly coherent vs. non-coherent MFSK receiver. It turns out that the auto- and cross-correlation properties of the eight (unknown to the receiver) random phase processes in the eight frequency slots influence the functional structure for the non-coherent MFSK receiver (Glenn, 1966; Filipowsky, 1969; Nesenbergs, 1971; Kwon and Shehadeh, 1975).

On the worst case basis, one may envision the eight random phases as wildly fluctuating and with no visible or useful cross-correlation properties. This may suggest the spectral energy (Lindsey and Simon, 1973; Ziemer, 1976) or envelope (Glenn, 1966) type of receiver. On the other hand, if the phases stay relatively constant over the 20 ms baud interval and display some mutual cross-correlation, then quadrature integration followed by weighted sums of square and linear terms may be preferable (Nesenbergs, 1971).

After detection (Figure 5), the 160 octal characters are converted back to 480 bits. These bits, in turn, must be un-interleaved before decoding. Figure 7 shows a standard matrix-type un-interleaver (also called de-scrambler). When the 480 bits exit from the un-interleaver, individual 24-bit codewords have been reassembled in 24-bit packages.

Next, the decoding of the (24, 12) code takes place, one codeword at a time. Perhaps the simplest of decoders for the (24, 12) code is shown in Figure 8. This decoder is of the syndrome matching type, as described

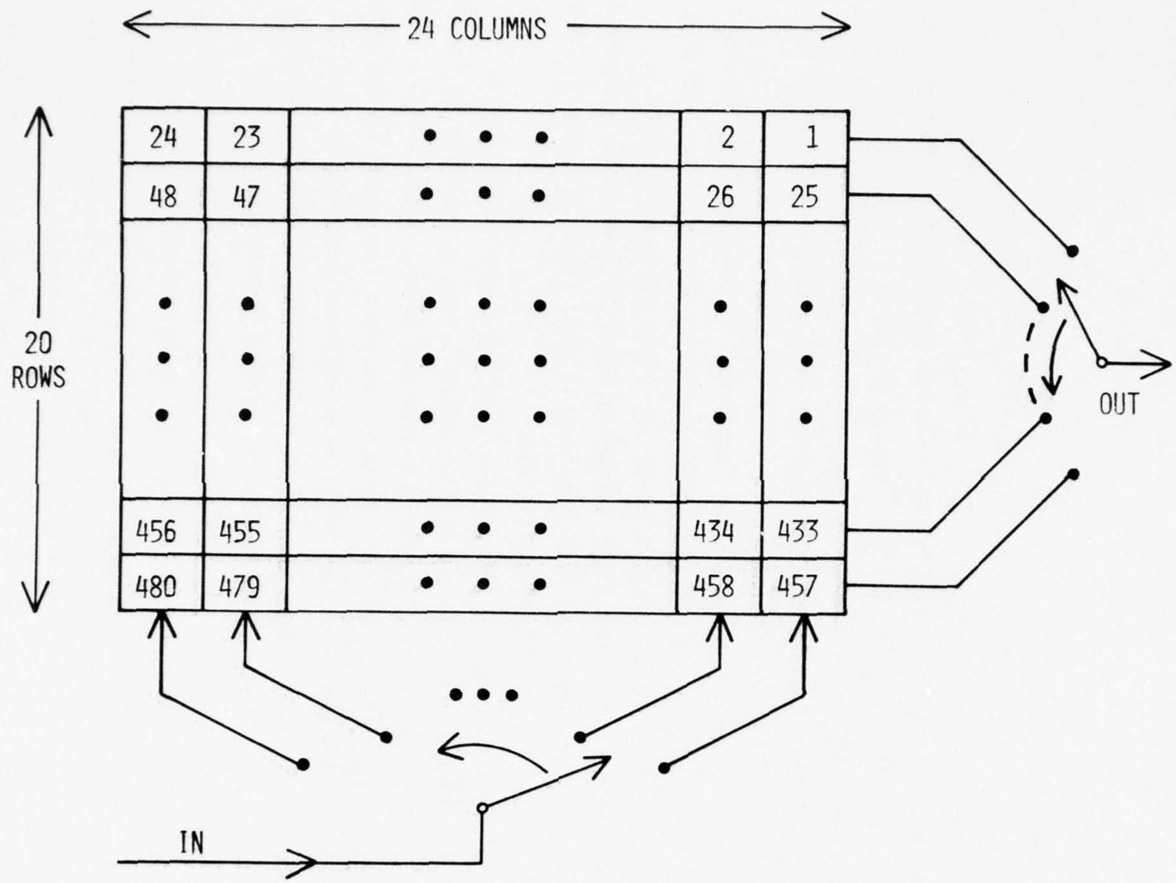


FIGURE 7. MATRIX TYPE UN-INTERLEAVER FOR THE (24, 12) CODE

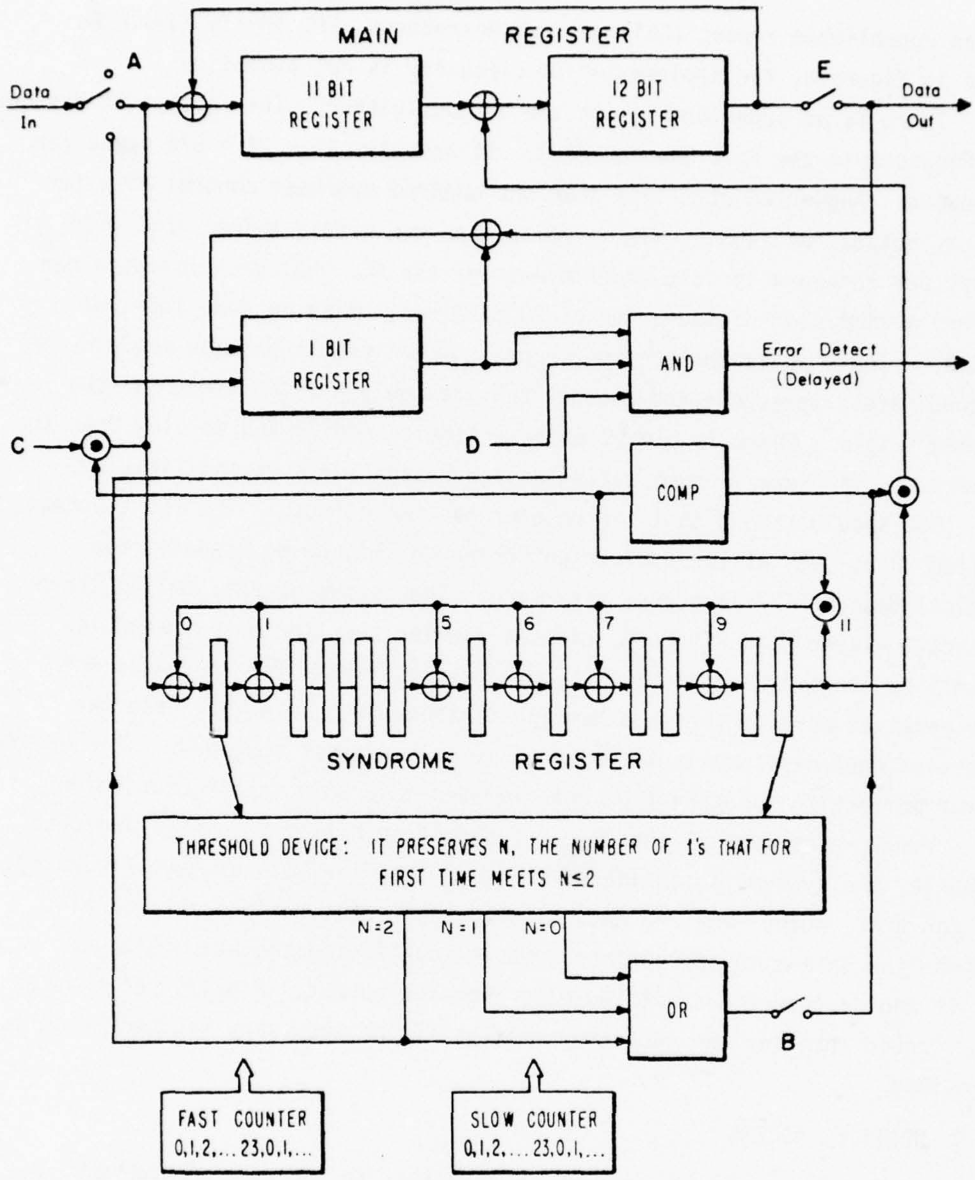


FIGURE 8. DECODER FOR THE (24, 12) CODE

in an unpublished report (Gallager and Nesenbergs, ERL TM-ITS 233). As seen in Figure 8, the implementation circuitry is not excessive.

There is no speed problem in the decoder either. The fastest of devices in Figure 8 is the Fast Counter (FC). It executes 24 x 24 = 576 steps per codeword. Augmented with less than one hundred overhead control bits for input, output, and sundry housekeeping, one can safely assume that 1000 steps per codeword is quite sufficient for the FC. But each codeword can occupy a time slot of the order of 28.6/20 sec, which is more than one second. Thus, while the present technology can easily process megabit per second rates, the suggested decoder requires only a kilobit rate of the decoder logic. There is plenty of real time to modify and to slow down the processes, if there is some system design reason for such modification.

One should stress that the decoder has two outputs. The first output, called "Data Out" at the upper right corner of Figure 8, produces the nominal decoded 12-bit output data word. The second output, called "Error Detect (delayed)" in Figure 8, gives a warning that the output word is likely to contain some errors. Such an event arises, for instance, when the received word is the same Hamming distance (e.g., in this case the shortest equi-distance is 4) from two or more nearest codewords. The entire error correction function then deteriorates to a coin tossing equivalent.

When one or more of the 20 error detection bits per message indicate trouble, the system is considered to be in the Alarm Status (see Figure 5). It can still output the 240 data bits to their destination. It can also append the data with appropriate symbols identifying the Alarm Status. Or it can disable the afflicted bits from the output. Finally, of course, the ground receiver can seek ARQ remedies if the necessary feedback link is provided.

3.6 MULTIPLE ACCESS

If many users desire to seek the services fo the same HF channel, and if their service times cannot be planned or controlled, multiple access problems arise. Contention for channel time takes place when messages overlap.

Multiple access issues can be introduced with the slotted-ALOHA example of Figure 9. As is known (Kleinrock, 1976; Schwartz, 1977), completely random or untimed ALOHA leads to throughput difficulties. Better operational efficiencies are realized by quantizing or slotting of time. Transmissions can commence only at certain specified times. If so, then messages fit into prescribed time slots or cells.

In Figure 9, the model is augmented to permit j, instead of one, frequency slots or channels. As shown, if a message overlap occurs in frequency slot i, a certain time gap is necessary before the involved transmitting parties can be apprised of the message conflict. After that, the parties are permitted to repeat their transmission, but according to some prescribed regime.

This regime specifies the frequency slot (1, 2, ..., j) and a new degree of freedom, the delay of the time slot (1, 2, ..., k), into which the retransmissions may take place. One regime can be a jk-ary random trial, where each of the jk-cells is picked independently and at random. Then, of course, secondary overlaps can occur with probability 1/jk and multiple repeats are a possibility.

For a single frequency slot, slotted-ALOHA, the effect of k is to increase the system throughput. This phenomenon is illustrated in Figure 10, together with the expected average message delay T.

One notes that, as a function of total channel traffic (i.e., throughput plus unsuccessful attemtps), the maximum slotted-ALOHA throughput occurs when there is approximately one packet on the air per cell, on the average. This throughput cannot exceed 1/e = 0.368, which is twice superior to the pure ALOHA. The optimal average delay is nearly T = 50 for both of the ALOHA's.

If in Figure 9, the gap and time cell duration is the same 30 sec, then for j = 1 the optimal average delay results in

$$1500\ (1 + \frac{2}{K})\ \text{sec} \geq 25\ \text{min.} \tag{4}$$

Such delays of half-hour duration may or may not be acceptable for the oceanic ATC application. This issue, together with an in-depth look at the multiple access system, remains to be resolved.

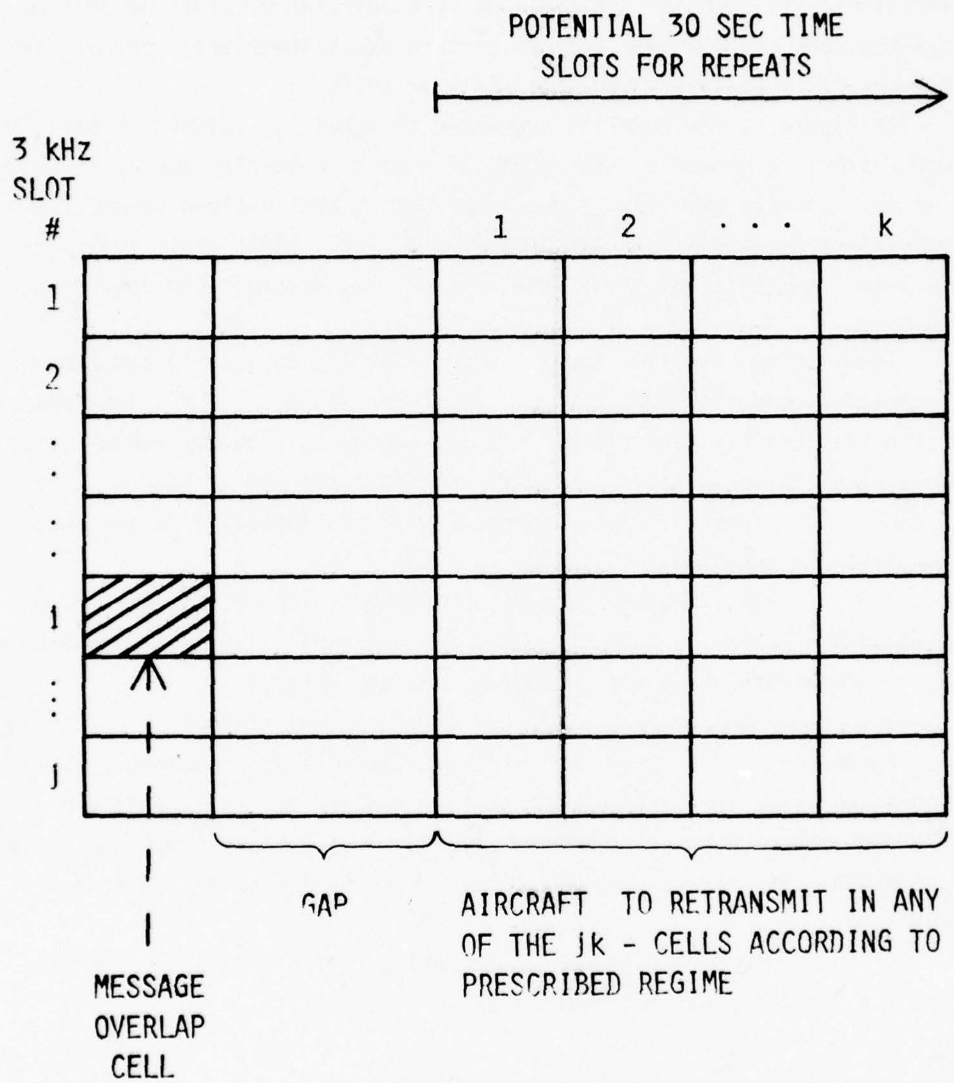


FIGURE 9. SLOTTED-ALOHA TYPE OF RETRANSMISSION

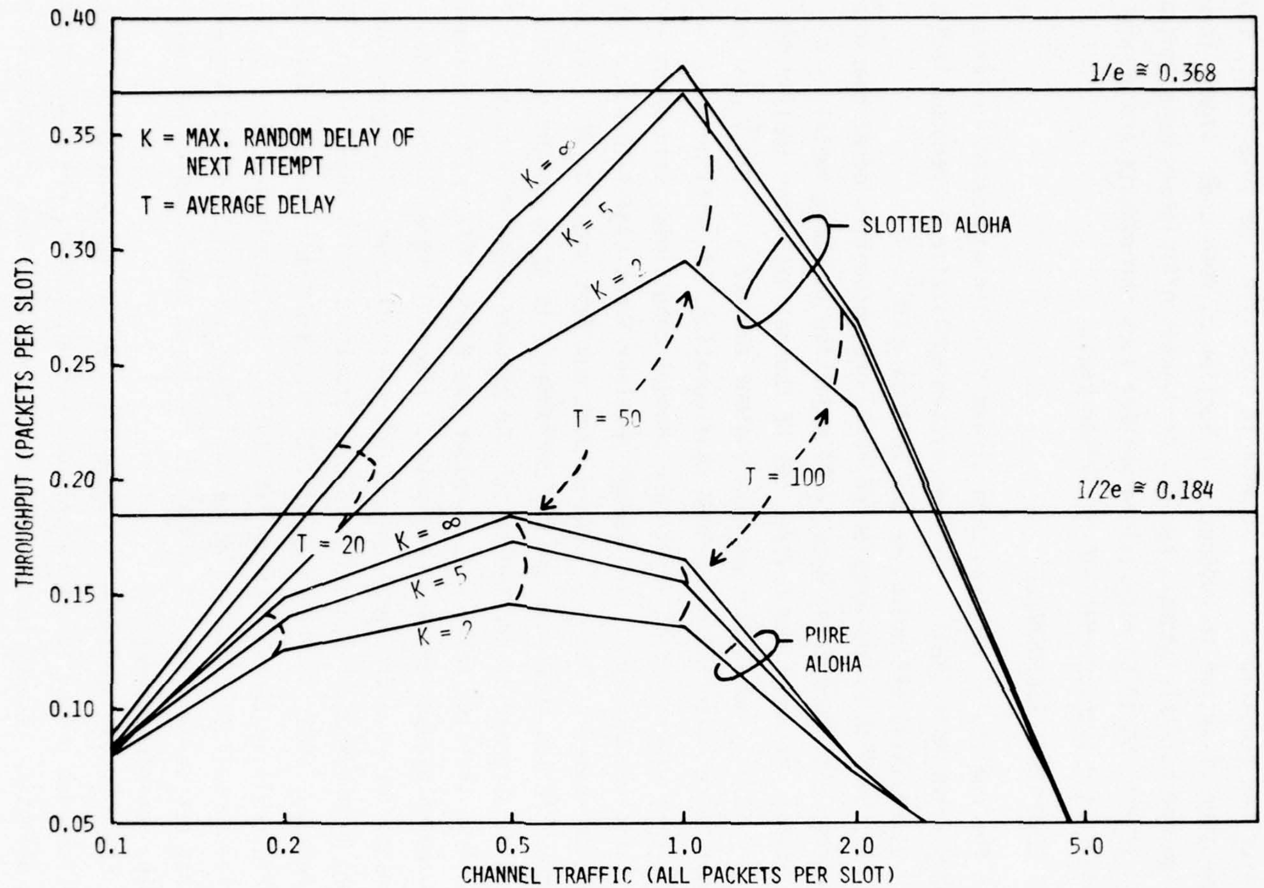


FIGURE 10. THROUGHPUT EFFICIENCY OF THE SLOTTED-ALOHA

4. OPERATIONAL ISSUES AND PERFORMANCE REQUIREMENTS

4.1 DATA THROUGHPUT

One of the foremost data system requirements concerns its ability to deliver the required volumes of data in specified time intervals. This is a question of system throughput. In Section 3, both under signal format design and multiple access, certain throughput efficiences were indicated.

It remains to be ascertained whether such throughputs are or are not adequate for transoceanic ATC HF system uses.

4.2 ERROR RATE PERFORMANCE

The quality of received data stream is often expressed in terms of Binary Error Rate (BER). For many system applications, perhaps including ATC, a realistic BER objective may well be $\leq 10^{-6}$.

In the MFSK system considered here, one encounters octal characters or words. The Word Error Rate (WER) objective is approximately $\leq 2 \cdot 10^{-6}$.

Since, as mentioned before, the HF channel has often implied BER $\cong 10^{-3}$, it is initially somewhat uncertain whether the WER $\leq 2 \cdot 10^{-6}$ goal can or cannot be met with the coded MFSK configuration. It will be shown next that, even under certain worst-case channel conditions, said error rate objective can be met if the average receiver input signal-to-noise ratio (SNR) expressed as ratio of powers, does not fall under 35 dB. The rest of this section shows how the WER performance is assessed and how the 35 dB requirement is arrived at for the assumed coded MFSK system.

As a starting reference, consider the M-ary, MFSK, WER performance for non-fading signals and Gaussian noise. Figure 11 shows such an ideal performance for several signal design and receiver cases. The curves are based on previous, relatively familiar studies (Turin, 1959; Glenn, 1966; Filipowsky, 1969; Nesenbergs, 1971; Lindsey and Simon, 1973). The ordinate in Figure 11 is the Word Error Rate (WER). The abscissa is the so-called normalized signal-to-noise ratio E_b/N_0, where E_b is the signal energy per information bit and N_0 is the noise power density per unit bandwidth, one-sided spectrum.

Four curves are shown in Figure 11. The two coherent detection curves are included primarily for reference. One notes that, while antipodal bit detection is superior to orthogonal waveforms, this advantage is more than lost when viewed within the possibilities of M-ary framework. Two

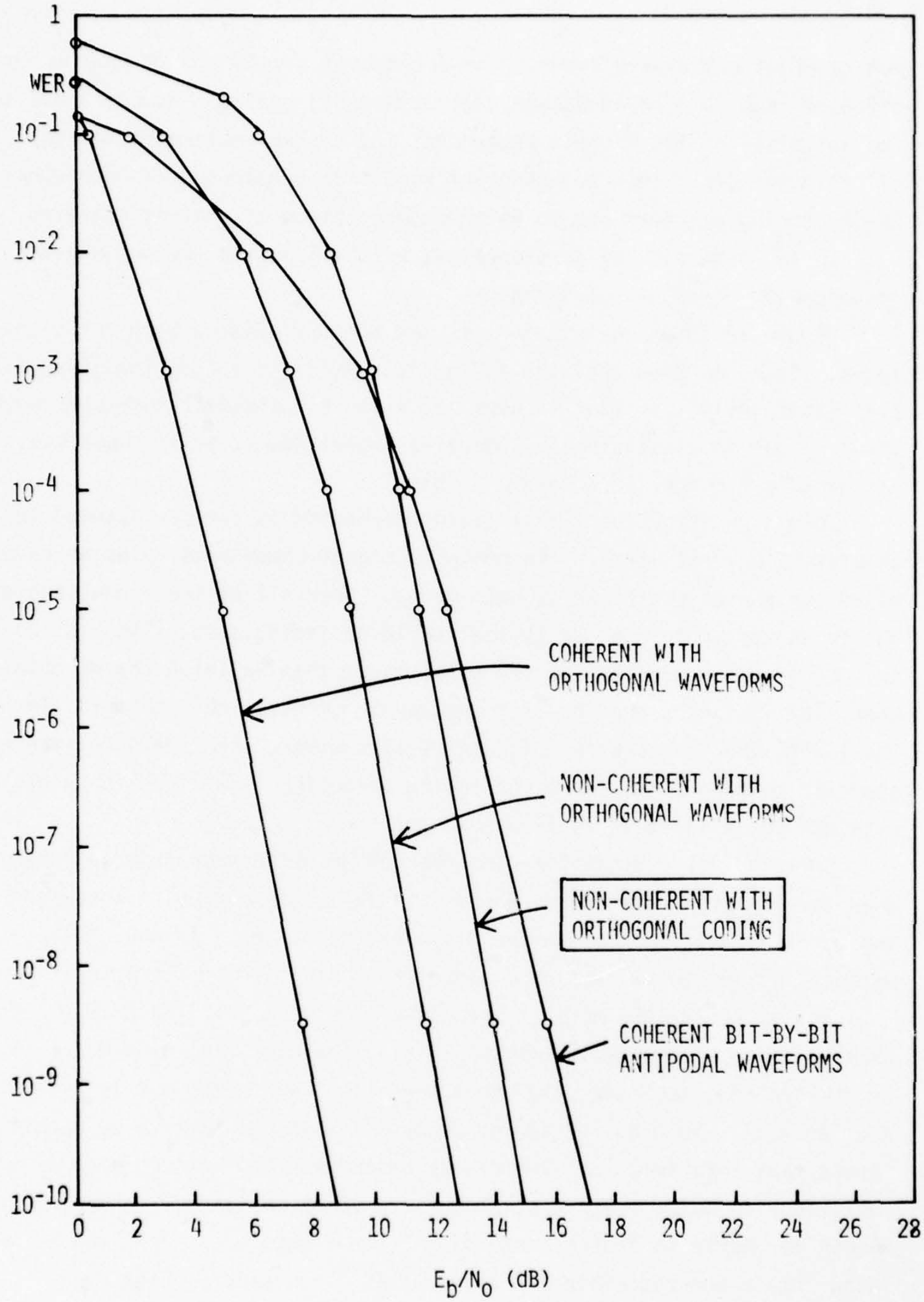


FIGURE 11. MFSK (M=8) WORD ERROR PROBABILITY FOR NON-FADING SIGNALS AND GAUSSIAN NOISE

non-coherent curves are shown. The orthogonal waveform case appears to offer at least a 2 dB advantage over orthogonal coding. However, due to instabilities of the M phase processes, the system implementation may prevent all its benefits. Then non-coherent reception combined with orthogonal ON-OFF coding may turn out to be more descriptive of what is achieved.

In the remainder of this section, we shall assume the non-coherent, orthogonally coded WER performance.

Figure 12 shows what happens to the WER performance when the signal fades. It is assumed that the fading is sufficiently slow (in time) and flat (spectrally), so that it does not distort individual character waveforms. Only the instantaneous received signal power, or its envelope, is going up and down in a random fashion.

This non-distortive signal fading mechanism is further assumed to consist of several mirror-like specular signal components, plus an undetermined portion of scattered signal energy. When all of the signal energy is due to scatter, one has the typical Rayleigh fading case. This is shown in the middle of Figure 12. Better performance than Rayleigh can be obtained when, for instance, one specular component dominates the scatter. In the limit, when the scatter disappears altogether, the remaining single specular component implies a non-fading situation. This best possible case WER curve is shown in Figure 12.

Unfortunately, digital fading channel HF performance can be even worse than for Rayleigh fading (Nesenbergs, 1967). This may arise when there are two nearly equal specular terms, plus lesser scatter. In what follows we shall assume this worst case specular-scatter fading characteristic.

In Figure 13, the model is rendered more realistic (Watterson and Minister, 1975) by introducing two elements. First, the Gaussian noise model is replaced by atmospheric, man-made, and other more impulsive noise models (see Section 2.2). Second, the fading process is made distortive by permitting intersymbol interference. The degree of intersymbol interference is shown to be equivalent to noise power that amounts to 10 dB margin for nonfading or 30 dB margin for Rayleigh fading performance (see Figure 12). This can be translated into a non-reducible WER level of 10^{-3}, as seen in Figure 13.

A 10^{-3} non-reducible WER or BER level is not atypical for long MFSK or binary FSK, HF paths. It cannot be effectively reduced by further increases in signal power or by lowering the receiver front-end noise

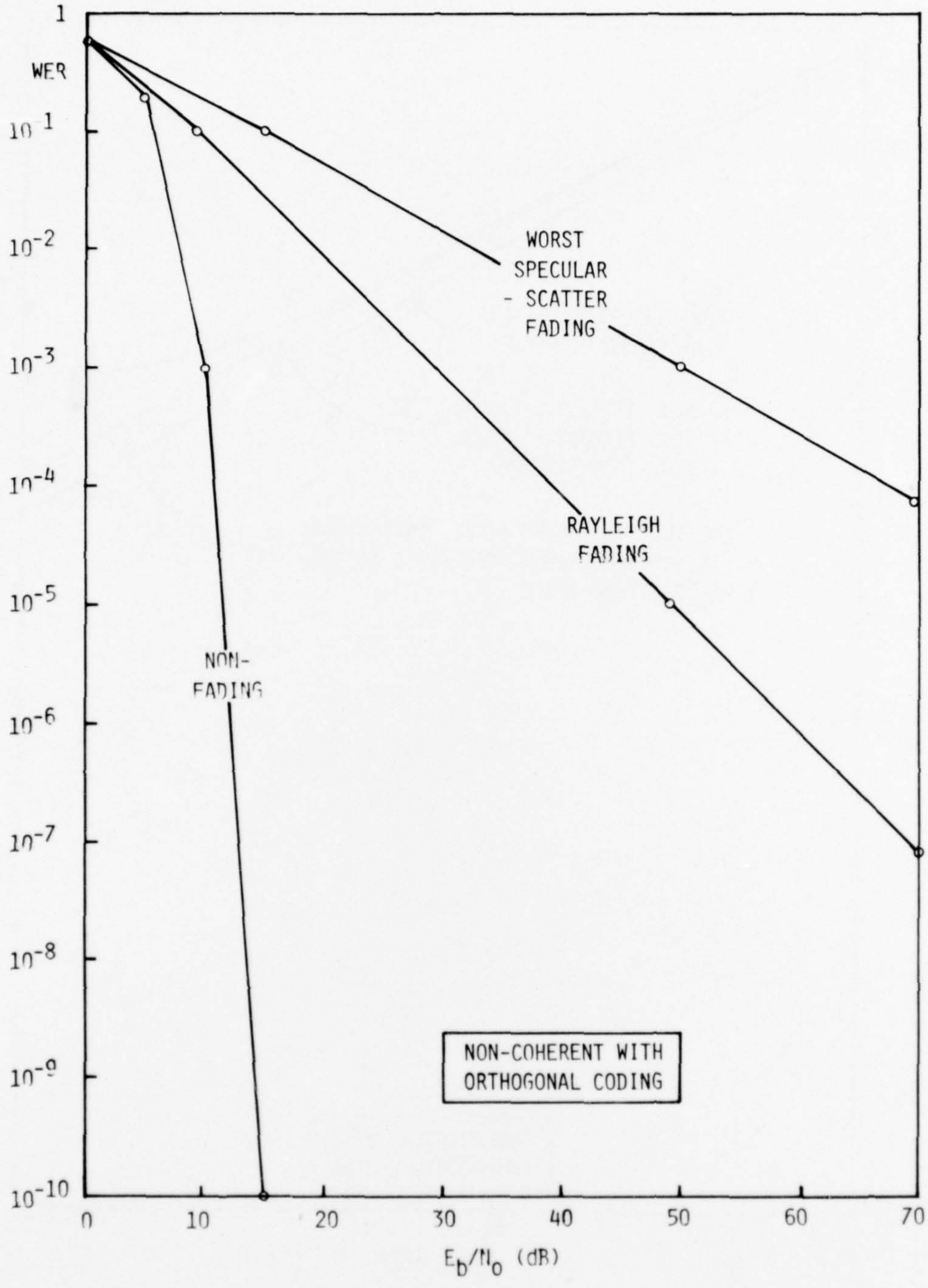


FIGURE 12. MFSK (M=8) WORD ERROR PROBABILITY FOR SLOW AND FLAT (NON-DISTORTIVE) FADING AND GAUSSIAN NOISE

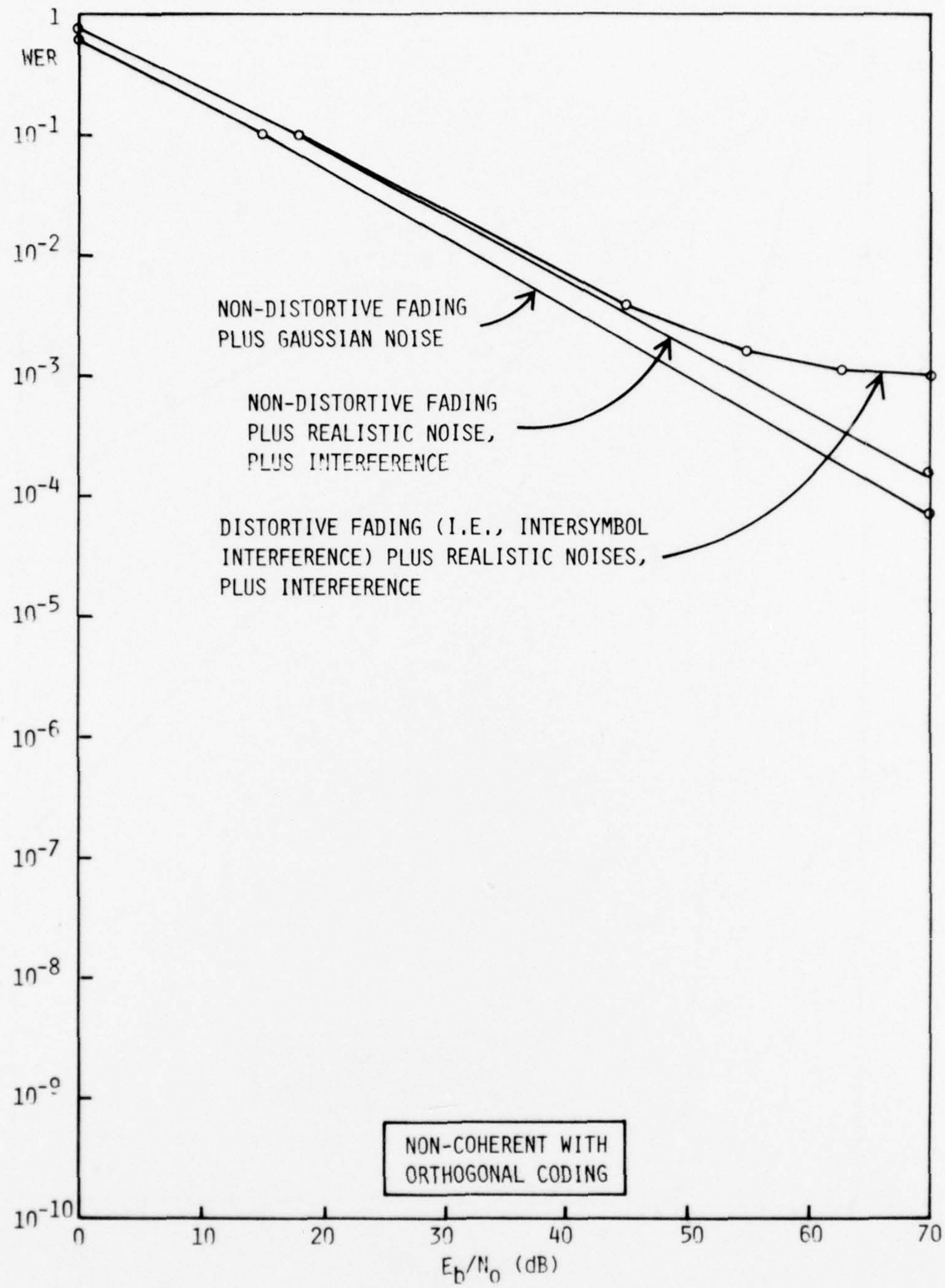


FIGURE 13. MFSK (M=8) WORD ERROR PROBABILITY FOR DISTORTIVE FADING WITH WORST CASE SPECULAR-SCATTER COMPONENTS, PLUS NOISES AND INTERFERENCE

temperature. Modem refinements are possible, but they tend to become more and more complex with questionable benefits.

The only alternative left seems to be error-control coding. Figure 14 shows the WER performance gains expected from the (24, 12) Golay code discussed earlier in Section 3.2. There are two coding curves, one for hard decision of each octal character, and another for soft (8-level) decision for the entire 8-character codeword. The numbers are based on predictions and observations made by numerous workers (Brayer and Cardinale, 1967; Cohn, et al., 1968; McManamon, et al., 1970; Pierce, et al., 1970; Brayer, 1971; Chien, 1971; Kuba and Lowry, 1971; Harper, 1974; Chase, 1975; Harper, et al., 1975; Ziemer, 1976; Chase and Bello, 1977; Jewett and Cole, 1978).

One notes from Figure 14 that there is no apparent coding gain for average normalized SNR under 20 dB. For SNR above 20 dB, the coding gain is a variable function of E_b/N_o, increasing from 10^{-1} WER reduction at 30 dB to 10^{-3} WER reduction at $\geq$ 60 dB.

The soft decision advantage is most noticeable between 30 and 60 dB SNR, where it is equivalent to no more than 1/2 of error rate, or 2-3 dB of SNR. For unlimited signal-to-noise ratio, WER can at best be 10^{-6}.

To summarize: For the MFSK system assumed here, the normalized SNR is:

$$\frac{E_b}{N_o} = \frac{P}{N} \cdot \frac{T_C W}{3} \qquad (5)$$

where P is signal power, N is noise power, T_C is character duration, and W is the effective MFSK bandwidth used. As discussed earlier in Section 3.4, T_c = 160 ms and W = 3 kHz may be realistic numbers. Then, for this case,

$$\frac{E_b}{N_o} = \frac{P}{N} + 22 \quad \text{(dB)}. \qquad (6)$$

Returning to the statement made in the early parts of this section, one sees that WER $\leq 2 \cdot 10^{-6}$ requires an E_b/N_o level of 57 dB for coded soft-decision operation. Hence, P/N should be 35 dB.

Further WER reduction appears very difficult, if not impossible, for the ordinary, badly behaved HF data channels.

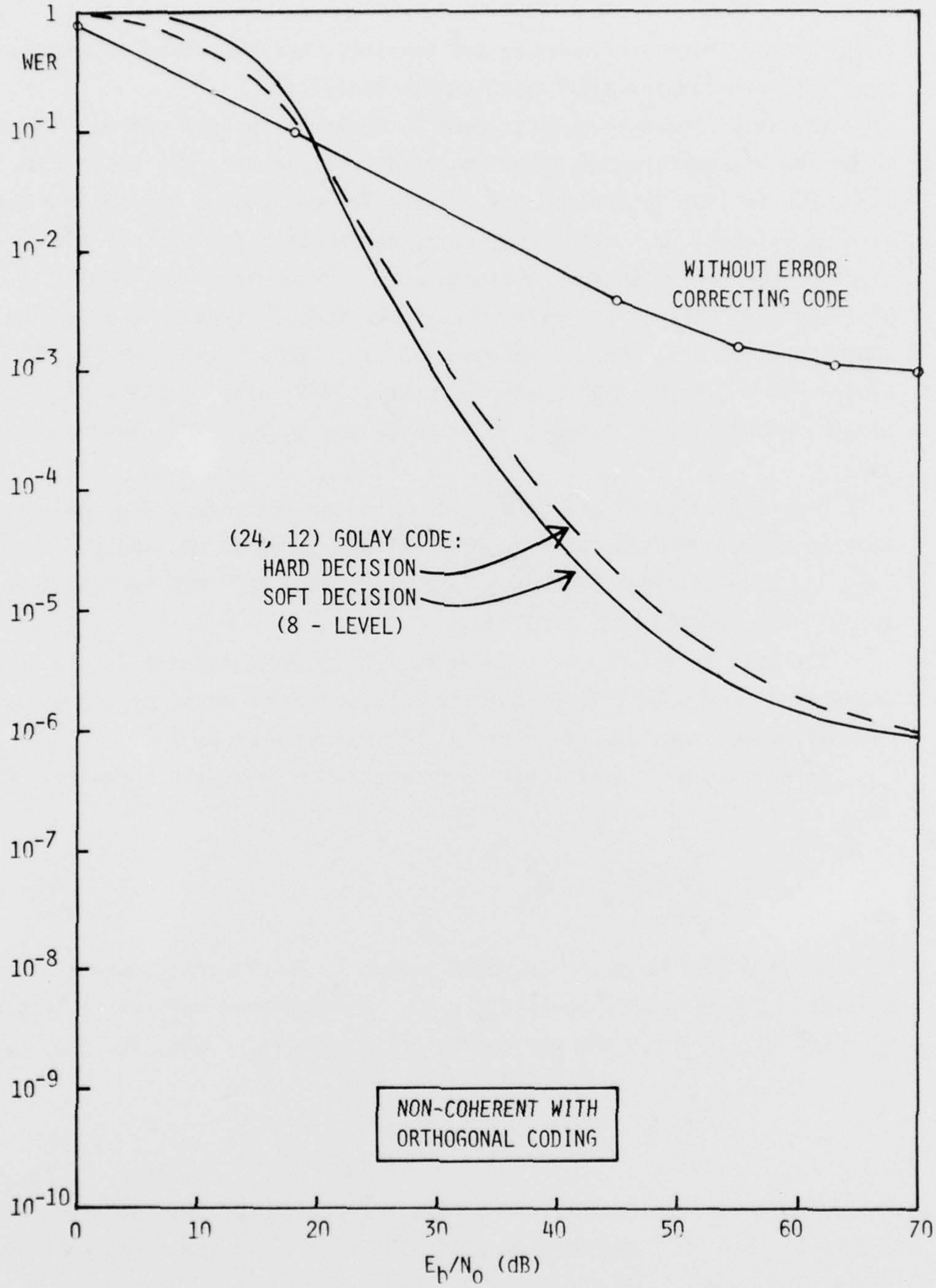


FIGURE 14. MFSK (M=8) WORD ERROR PROBABILITY FOR DISTORTIVE WORST-CASE FADING WITH REAL NOISES AND INTERFERENCE

5. CONCLUSIONS

5.1 SUMMARY

This short study has tried to assess potential use of HF data transmissions for transatlantic ATC applications and service improvement. Because of the imposed time and resource constraints, this study was brief and limited in several respects.

It was necessary to delete such important topics as present and future trends in transatlantic air traffic, the anticipated ATC message mixes and volume statistics, the role of HF vs. VHF, the characteristics of existing and proposed SSB modems, as well as the overall ATC objectives for HF channels (when contrasted in particular with available satellite options).

In absence of specific performance requirements, operational performance issues such as general grade of service (i.e., traffic engineering for probability of blocking and desired delay statistics), as well as incorporation of mandatory and prevailing ATC system practices, were not covered. Related performance issues on data throughput and multiple access requirements were treated in a very cursory fashion.

The approach taken here emphasized several items:

1) HF is an extremely complicated medium for data communications;
2) there are many system approaches, known and proposed;
3) ATC objectives may benefit from a parametric approach that proceeds from a broad conceptional base to specific system definitions; and
4) the utility of this approach was demonstrated by defining and discussing a specific coded MFSK communication system.

To ascertain whether HF is appropriate for transatlantic ATC objectives, one must be aware of HF limitations. These limitations can be both messy and severe (see Figures 11 through 14). It is well known that HF can do just so much and no more. To see exactly how much and in what respect, one must address specific objective issues. That is the topic of the next and final section.

5.2 ISSUES: RESOLVED, PARTLY RESOLVED, AND UNRESOLVED

From the discussion given above, it appears that there are many issues that require discussion, review, and eventual resolution. The issues can be divided into several categories. First, there are general administrative

issues including organizational responsibility, policy, and future roles. Second, there are user-oriented or service issues that depict the system as seen by someone on the outside. Finally, there are the many issues that concern the intrasystem elements and their roles. The latter are typically technical and system-oriented.

A brief summary of the HF data transmission issues for transatlantic ATC application is given in Tables 3 and 4. Table 3 lists the general and service-oriented issues. Table 4 lists the technical and system-oriented issues. They all require resolution, albeit to quite different degrees.

TABLE 3. GENERAL AND SERVICE ORIENTED ISSUES

1. International Policies and Agreements

2. Geographic Responsibilities

3. Present and Future Roles of HF

4. Interfaces with Other Systems

5. Constraints of Practice and Cost

6. Service Requirements:

   Traffic Scenarios
   Traffic Demands
   Grade of Service Objectives
   Delay Objectives
   Availability and Integrity

7. Service Oriented Test Programs

8. Eventual Implementation and Growth

TABLE 4. TECHNICAL AND SYSTEM ORIENTED ISSUES

1. HF Band (2.8 - 24 MHz) Allocations
2. Time-Varying Channel Characteristics
3. Voiceband Compatibility
4. Airborne vs. Ground Terminal Simplicity
5. Integrity Assurance: ACK, ARQ, Monitoring and Backup Systems
6. Multiple/Random Access Schemes
7. Severity of Co-Channel Interference
8. System Requirements:
    - Aircraft Terminal Interfaces
    - Ground Terminal Interfaces
    - Required Functions
    - Distribution of Control
    - Memory and buffers
    - Offered Loads
    - Data Rates
    - Protocols and ACK's
    - Error Controls (FEC, ARQ, Hybrid)
    - Coded Non-Coherent MFSK
    - Time-Bandwidth Profile
9. Modem and Codec Strategies:
    - Frequency Agility vs. Interference
    - Baud Stretch vs. Delay Distortion
    - Interleaving vs. Deep Fades
    - Extra Parity vs. Outages

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